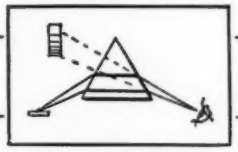
Journal of the OPTICAL SOCIETY *of* AMERICA

VOLUME 25
No. 7



JULY
1935

Quantum Efficiency of Certain Light Sensitive Devices . . . C. C. HEIN 203

Optical Properties of Magnesium Oxide . JOHN STRONG AND R. T. BRICE 207

Interpretation of Data Obtained with Spectrophotometers of the Polarizing Type . . . . . ROBERT D. NUTTING 211

Fatigue of the Extrinsic Ocular Muscles While Reading Under Sodium and Tungsten Light . . . . . M. LUCKIESH AND FRANK K. MOSS 216

Recording Goniophotometer . . . . . JOHN M. SLATER 218

Back Numbers of J. O. S. A. Wanted 223

Annual Report of Secretary O. S. A. for 1934 224

Annual Report of Treasurer O. S. A. for 1934 226

Published monthly
at Prince and Lemon Sts., Lancaster, Pa.
by the
AMERICAN INSTITUTE OF PHYSICS
Incorporated
11 East 38th Street, New York, N. Y.
FOR AND UNDER THE EDITORIAL SUPERVISION OF
THE OPTICAL SOCIETY OF AMERICA

THE OPTICAL SOCIETY OF AMERICA

OFFICERS OF THE SOCIETY

W. B. RAYTON, *President*
Bausch & Lomb Optical Company
Rochester, New York

ARTHUR C. HARDY, *Vice President*
Massachusetts Institute of Technology
Cambridge, Massachusetts

L. B. TUCKERMAN, *Secretary*
Bureau of Standards
Washington, D. C.

HENRY F. KURTZ, *Treasurer*
Bausch & Lomb Optical Company
Rochester, New York

The Board of Directors consists of the above officers; the Editor of the Journal; the Past President; and five elected members:

E. C. CRITTENDEN, *Past President*
Bureau of Standards
Washington, D. C.

F. K. RICHTMYER, *Editor*
Cornell University
Ithaca, New York

Elected Members

ARTHUR H. COMPTON
Ryerson Physical Laboratory
University of Chicago
Chicago, Illinois

HERBERT E. IVES
463 West Street
New York, New York

CARL W. KEUFFEL
Keuffel & Esser Company
Hoboken, New Jersey

GEORGE B. PEGRAM
Columbia University
New York, New York

R. C. GIBBS
Department of Physics
Cornell University
Ithaca, New York

THE OPTICAL SOCIETY OF AMERICA was organized in 1916 "*to increase and diffuse the knowledge of optics in all its branches, pure and applied, to promote the mutual interests of investigators of optical problems, of designers, manufacturers and users of optical instruments and apparatus of all kinds and to encourage cooperation among them.*" It aims to serve the interests of all who are engaged in any branch of optics from fundamental research to the manufacture of optical goods.

MEMBERSHIP

Regular Members: "Any person who has contributed materially to the advancement of optics is eligible for regular membership."

Associate Members: "Any person who is interested in optics is eligible for associate membership."

Corporate Members: "Any corporation desirous of encouraging the work of the Society is eligible for corporation membership."

The Society cordially invites to membership all who are interested in any branch of optics, either in research, in instruction, in optical or illuminating engineering, in the manufacture and distribution of optical goods of all kinds or in physiological and medical optics.

ANNUAL DUES

Regular members, $7.50; Associate members, $5.00; Corporate members, $50.00. These dues include subscription to the Society's official journal, the *Journal of the Optical Society of America.*

MEETINGS

The Society holds two meetings per year: An annual meeting in the autumn and a midwinter meeting jointly with the American Physical Society.

For further information concerning the Optical Society of America address the Secretary, Dr. L. B. Tuckerman, Bureau of Standards, Washington, D. C.

ROCHESTER, NEW YORK SECTION OF THE OPTICAL SOCIETY OF AMERICA

C. C. NITCHIE, *President*
H. E. SEEMANN, *Secretary*

L. A. DUBRIDGE, *Vice President*
H. G. KINGSLAKE, *Treasurer*

Councilors: E. C. FRITTS, R. KINGSLAKE, H. F. KURTZ, T. R. WILKINS, C. J. STAUD (*ex-officio*)

Journal of the
OPTICAL SOCIETY *of* AMERICA

VOLUME 25 JULY, 1935 NUMBER 7

Quantum Efficiency of Certain Light Sensitive Devices

C. C. HEIN, *Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania*

(Received March 26, 1935)

Quantum efficiency of a light sensitive device is defined as the number of electrons released per unit incident quantum. Values of efficiencies are obtained from spectral response curves plotted in absolute values. The necessity of absolute values requires the use of a calibrated thermopile. The calibration of the thermopile and the method for obtaining spectral response curves are described. Curves are plotted for the visible region giving the maximum theoretical yield and also the yield and quantum efficiency for two types of Photox, two types of selenium photovoltaic units, a cesium oxide phototube and the thermopile. The maximum yield for photovoltaic units is found to range from 0.045 to 0.125 ampere per watt with a quantum efficiency range of from 9 to 28 percent. The maximum visible yield of the cesium oxide surface is 0.002 ampere per watt and a quantum efficiency of 0.4 percent, while the thermopile yield is 0.022 ampere per watt with an efficiency of 5 percent.

IN recent years there has been considerable advancement in obtaining increased current output from photoelectric surfaces. This advancement came as a result of extending the red sensitivity of the device rather than an increase in output in the visible region. The advent of photovoltaic cells of the rectifier type brought current outputs of the order of tenths of a milliampere per lumen obtained primarily from visible radiation. The production of a visibly activated cell having considerably higher current output than the phototube depending on infrared sensitivity to bolster its response is the result of an increased quantum efficiency.

Quantum efficiency is defined in terms of electrons released per unit incident quantum. It is obvious that 100 percent efficiency corresponds to the release of an electron for each incident quantum, 25 percent efficiency would mean the release of one electron for each four impinging quanta.

The spectral response curves of light sensitive devices depict the liberation of electrons for various wavelengths of radiation. If these curves are given in absolute units, amperes per watt, then it is possible to obtain the quantum efficiency directly. The maximum value of the current per watt is obtained by assuming the release of an electron for each quantum and is expressed as

$$\text{amp./watt} = 10^7 e\lambda/hc.$$

The absolute value of the spectral response curve represents a percentage of the maximum obtainable value and this percentage is the quantum efficiency for that particular wavelength.

The absolute value of the spectral response curve determines the response of that unit for any particular wavelength and the area under the composite curve obtained by multiplying the spectral response curve by the energy distribution curve of the light source is an expression for the output of that unit for such illumination.

BOSTON UNIVERSITY
COLLEGE OF LIBERAL ARTS
LIBRARY

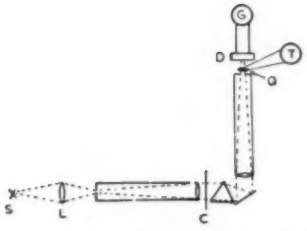


FIG. 1. Schematic diagram of apparatus used to determine spectral response curves.

This expression has been termed the sensitivity of the light sensitive device and is usually expressed in microamperes per lumen. The output of a photoemissive tube is directly proportional to its sensitivity. Hence for a given load resistance the voltage output will be a function of the sensitivity. Phototubes are generally used as grid impedances in conjunction with thermionic tubes and so the quantum efficiency determines the available grid swing.

Photovoltaic units operate instruments and relays directly and power output is of prime importance. The power output for these units is a function of open circuit voltage and short circuit currents. It is not directly proportional to the sensitivity, but it is a function of the sensitivity and hence of the quantum efficiency.

A determination of quantum efficiencies may be accomplished by absolute determinations of spectral response curves of the devices in question. To accomplish this end the current response of the unit must be observed and the energy producing this response measured in absolute values.

The method for obtaining spectral response curves will now be given.

Fig. 1 is a schematic diagram of the set-up. The radiation from a voltage controlled light source S is focused by lens L onto the slit of a monochromator. The output of the monochromator filters through a thermopile Q connected to galvanometer T and impinges on the light sensitive device D whose response is measured by the deflection of the galvanometer G. The wavelength to be investigated is selected on the monochromator wavelength drum and then the cut-off C is raised, permitting the radiation to fall on the light sensitive device D. The

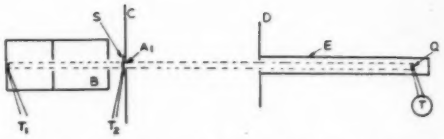


FIG. 2. Schematic diagram of apparatus used for thermopile calibration.

deflections of T and G are noted. Knowing the constants of G and of the thermopile the response for that particular wavelength is determined directly. This procedure is followed for various wavelengths until sufficient points have been obtained to plot the curve. The constant G can be determined by comparison with known currents. The constant of the thermopile may be determined by comparison with a previously calibrated standard radiation source or by reference to a black body.

The latter method is of interest and will be described. Fig. 2 gives a schematic diagram of the method employed. A suitably constructed black body B is used as a source of radiation. The temperature of this body is measured by the thermocouple T_1. Q is the thermopile to be calibrated and is well shielded from spurious radiation and air currents by the tube E and by shields C and D. A_1 is a definite aperture in

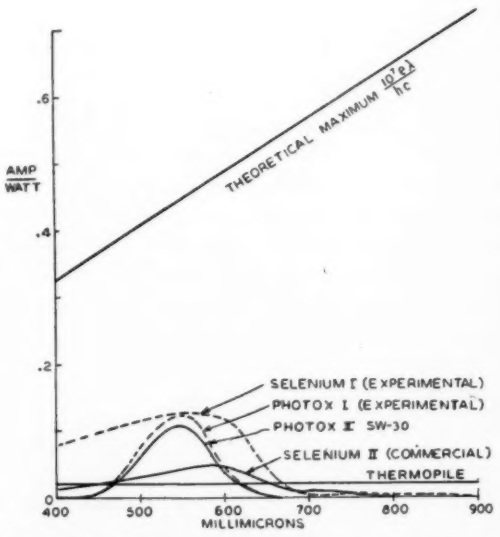


FIG. 3. Absolute spectral response curves for various light sensitive devices.

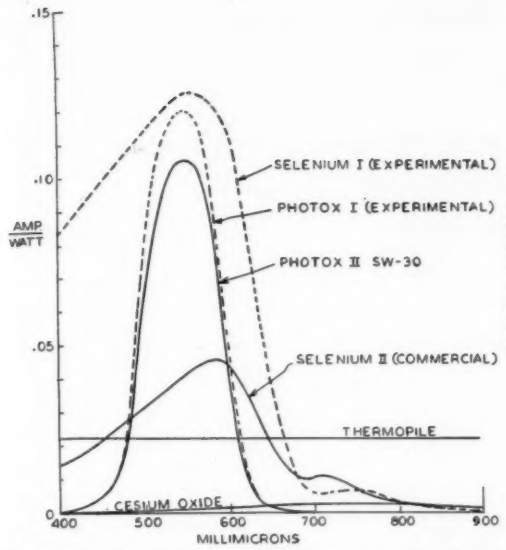


FIG. 4. Absolute spectral response curves for various light sensitive devices.

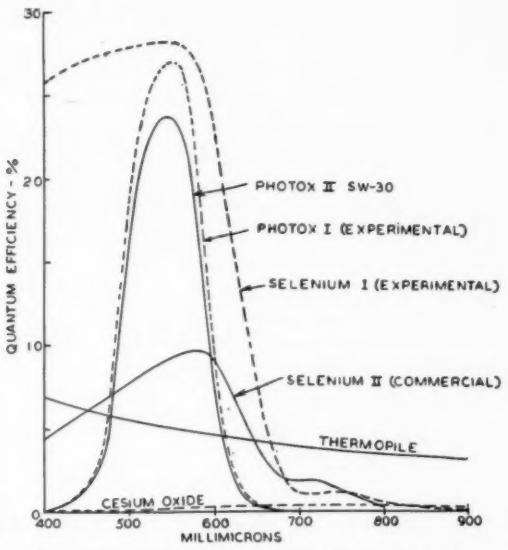


FIG. 5. Quantum efficiency curves for various light sensitive devices.

shield C and is considered as the source in this calibration. S is a smoked metal shutter with attached thermocouple used to cut off the radiation from B and in turn act as a second black body whose temperature is measured by T_2. A_1 is an eighth-inch hole and the distance A_1 to Q 60.4 cm. The responses of the thermopile Q to the two black bodies at temperature T_1 and T_2 are sufficient for calibration. The expression for the black body radiation difference is given as

$$Q=\sigma(T_1^4-T_2^4)A_1A_2/\pi D^2,$$

in which A_2 is the area of the thermopile and σ is the Stefan-Boltzmann radiation constant. T_1, T_2 and the deflections corresponding to T were noted for a series of temperatures ranging from room temperature to 1000°C. Differential thermopile deflections Q were plotted against the differences of the fourth powers of the absolute temperatures $(T_1^4-T_2^4)$ and the value of the slope, $(T_1^4-T_2^4)$ per unit deflection of Q, determined. D was measured directly and A_1 and A_2 by means of projected images traced with a planimeter and reduced by the proper ratio. Thus the energy per unit deflection of Q was obtained and the thermopile calibrated. In Fig. 1 only a small portion of the energy incident on Q trickles through and impinges on the light sensitive device. This percentage of the total energy incident upon Q trickling through onto the unit was determined from the projected image of the thermopile by planimeter measurements. Thus an accurate measurement of the energy incident upon the light sensitive device is obtainable.

Absolute spectral response curves were obtained for two types of selenium photovoltaic cells, two types of Westinghouse Photox, a cesium oxide phototube and the thermopile.

Fig. 3 gives the response curves obtained and the theoretical maximum. The cesium oxide surface has a response of the order of 0.002 ampere per watt and hence would appear as a curve barely noticeable above the zero line. It is obvious that there is still considerable room for advancement in the visible and infrared regions. Fig. 4 gives the absolute response curves on an expanded scale. From Fig. 3 it is possible to obtain the quantum efficiencies, and these are given in Fig. 5. Several of the photovoltaic units are beyond the 25 percent value at their maxima while the thermopile quantum efficiency ranges from 3 to 7 percent for the visible region and the cesium oxide phototube yields a maximum value of 0.38 percent at its maximum.

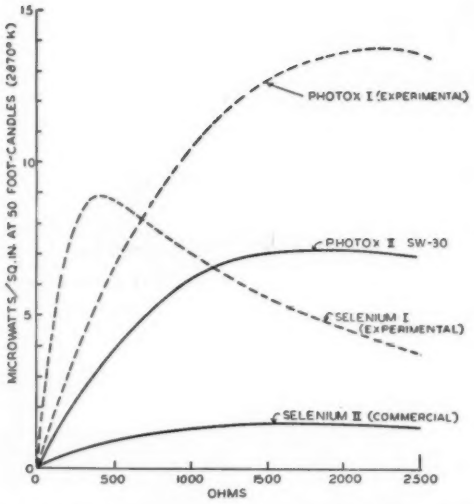


FIG. 6. Power output per unit area at 50 footcandles for various types of photovoltaic cells.

The curves for the photovoltaic units in Figs. 3, 4 and 5 give current values for various wavelengths. In practice these devices are used with radiation from tungsten lamps and hence it is of interest to compare usable power output at a convenient intensity, say 50 footcandles. Fig. 6 gives the power output per square inch for each of the four photovoltaic units. "Photox I (experimental)" affords a power output of nearly 14 microwatts per square inch of active area while the standard "Photox II SW–30" has a value of 7 microwatts per square inch. The "Selenium I (experimental)" yields 9 microwatts per square inch and "Selenium II (commercial)" gives 1.5 microwatts per square inch. These values are of prime importance since photovoltaic units are used with relays and meters where power output is the significant factor.

TABLE I. *1 Lumen from tungsten lamp at a color temperature of 2870°K.*

Type	Short circuit (microamperes)		Microwatts	Volts
Photox I (experimental)	200	40	0.50	Open circuit
Photox II SW-30	150	20	.35	
Selenium I (experimental)	450	25	Maximum .16	
Selenium II (commercial)	120	5	.15	
Phototube	20		0.8 2000 ohms	20 volts/megohm
Thermopile	37		0.022 max.	0.001 open circuit

A general comparison of all the devices investigated may be made by assuming 1 lumen of radiation from a tungsten lamp operating at a color temperature of 2870°K falling on each of the units and then obtaining values for short circuit current, voltage and power output. These are given in Table I.

Industrially the thermopile, although having a constant response curve with respect to spectral frequency, and a fair value of quantum efficiency is certain to remain a laboratory device because of its inherently low characteristics.

The phototube is a high impedance device and should not be considered as a power developing unit. In grid circuits it affords high voltage outputs with low light values and the developed voltage is dependent only upon the value of grid resistance consistent with stable tube operation.

The photovoltaic devices are industrially attractive because of their relatively high power output which obviates the need of voltage supply and sensitive galvanometer.

The writer wishes to make acknowledgment to Dr. E. D. Wilson, who directed the investigation.

Optical Properties of Magnesium Oxide*

JOHN STRONG AND R. T. BRICE, *California Institute of Technology*

(Received March 20, 1935)

It is pointed out that crystals of β-magnesia of optical quality may be obtained in sizes up to 1½ inches diameter. Windows for use in spectroscopic furnaces have been prepared from this material. Tests made with these windows show that they resist attack by the vapors of Ca, Na, K and Li. They transmit from 2150A in the ultraviolet to about 5 μ in the infrared. The index of refraction varies from 1.8450 at 2536A to 1.7313 at 7065A. The dispersion, ν, is 53.5. A preliminary investigation shows that it may be suitable for a quartz-magnesia doublet lens.

INTRODUCTION

IT has been known for some years that β-magnesia (MgO), or periclase, exhibits some interesting and useful properties which make it suitable for windows for use in spectroscopic investigations at high temperatures. It is not generally known, however, that it is now available commercially. At the present time β-magnesia is manufactured for use as an electrical insulator of high thermal conductivity. It is also used as a refractory material for making crucibles. The material comes from the electric fusing furnaces in ingots weighing several tons which are subsequently ground to a fine powder. Little or no attention is paid to the optically clear crystals which occur in a band about 3 inches from the outside of the ingot. These crystals comprise only a very small portion of the ingot, and are frequently ground up along with the remainder of the ingot which is milky and often discolored by impurities.

Up to the present time the largest single crystals obtained by the authors measured 1½ inches on the edge of a square face of ⅜-inch thickness. These crystals were supplied by the Norton Company and accompanied by the following chemical analysis:

SiO_2	0.04 percent
Fe_2O_3	0.04 percent
CaO	0.04 percent.

In a letter concerning this particular shipment of crystals, Mr. Raymond R. Ridgway of the Norton Company's Research Laboratories says: "They are formed by differential crystallization, so that they do not contain as much impurity as the original melt." In view of the fact that they appear accidentally in large scale production, and since the crystals are always of greater purity than the remainder of the ingot, it is reasonable to believe that a melt whose temperature and purity were carefully controlled might furnish much larger crystals than those heretofore found.

The crystals used for the windows and prisms in the following experiments were selected from this same shipment. Similar crystals of optical quality have been obtained from the General Electric Company and the Vitrefax Corporation. The present commercial value of the optically clear crystals is about $1.00 per pound. The density of the crystals is about 3.55.

β-Magnesia is easy to work optically. The hardness is about the same as quartz. Water may be used while grinding and polishing. The crystals may be readily cleaved to the approximate size desired. After grinding to shape they are fine ground with number 600 carborundum and polished with tin oxide. Emery was not used because it caused the surface to flake and scratch. Rouge was found inferior to tin oxide for polishing. Unless great precision is required, windows may be quickly polished on a fast soft-pitch lap.

ACTION OF METAL VAPORS ON β-MAGNESIA WINDOWS

The effect of heat alone on β-magnesia begins to be apparent about 2100°C where sublimation sets in. The crystal melts at 2800°C. A small piece of β-magnesia heated to incandescence to the limit of an oxyacetylene flame and allowed to cool in air gave evidence of sublimation but was otherwise unaffected. The crystal may be heated

*Read before the American Physical Society in Los Angeles, December 1934.

rapidly but must be cooled slowly. One piece was heated to 100°C and immersed in cold water. It shattered into many small cubes.

β-magnesia is not immune to the effects of CO_2 in the atmosphere where, in the presence of water vapor, it is gradually carbonated on the surface. This reaction is a very slow one and no carbonate was observed to form on the prisms throughout the time involved in the measurements. Polished windows lost their polish in moist air in from 2 to 6 months depending on the humidity. In a desiccator the window surfaces keep their polish indefinitely insofar as we may judge from our experience. One window which was sealed into an evacuated tube lost none of its polish in five months. The windows tested with metal vapors were washed in water to remove solid metal. No apparent effect of the washing on the polish was observed. Likewise, samples washed in H_2SO_4, HNO_3, HCl, chromic-sulphuric acid cleaning solution, NH_4OH, and NaOH all came out unaffected. A piece immersed in concentrated HNO_3 overnight was not visibly affected.

Six windows, 12.5 mm diameter by 2.5 mm thickness, were cut from single crystals of β-magnesia. These windows were placed, two at a time, inside a vacuum furnace containing about a gram of an alkali metal. The temperature was slowly raised until the vapor pressure of the alkali metal was approximately 1 cm and after exposure to the metal vapor overnight the windows were removed and examined.

With calcium it was possible to compare the effect of the vapor on magnesia with its effect on sapphire. A sapphire window was placed in one end of the furnace and a β-magnesia window in the other end. The sapphire was rendered opaque and eaten out to a depth of about 1 mm while the β-magnesia window was quite unaffected. A photograph of the sapphire window is shown in the upper right-hand corner of Fig. 1.

Sodium and potassium showed practically no effect on the β-magnesia. Lithium vapor showed a slight reaction with the window. The extent of this reaction is shown in Fig. 1. It is evident by comparison of these photographs, showing writing on a paper disk under each window, that the reaction with these alkali metal vapors was slight. An unused window is shown for comparison and marked "clear." Even the reaction of lithium is not sufficiently violent to preclude the use of β-magnesia windows with this metal.

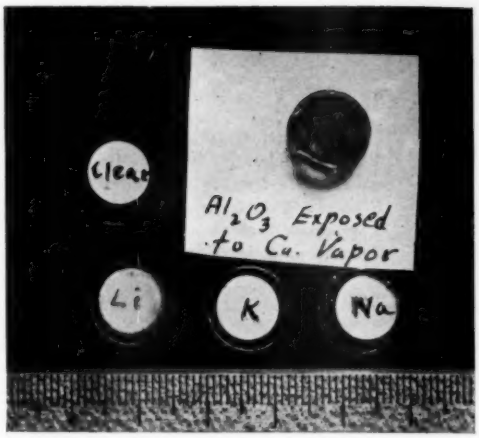


FIG. 1. Windows used in tests of corrosive metals on β-magnesia.

The windows were not protected from the condensation of molten metal upon their surface and so, in each case, drops of the metal collected on the windows during the tests. The outer layer of the metal used to charge the furnace was somewhat oxidized. It is therefore probable that the conditions which obtained in these tests represent the least favorable conditions under which the windows would be used as far as impurities are concerned. Table I lists the data for these tests with corrosive metals.

If the magnesia window is not vacuum tight it is advisable to use the β-magnesia in conjunction with a quartz window. The β-magnesia is placed inside and exposed to the corrosive vapor, whereas the quartz window is outside and used to maintain the vacuum in the furnace.

TABLE I. *Results of exposure of β-magnesia windows to hot alkali-metal vapors.*

Metal	Maximum temperature	Duration of exposure	Results
Ca	810	36 hours	No attack
Na	610	1 hour	No attack
	200	24 hours	Slight attack
K	450	24 hours	No attack
Li	500	3 hours	No attack
	688	22 hours	Surface etched Window not opaque

One significant physical property of β-magnesia is its coefficient of thermal expansion. The value of this constant is 11.4×10^{-6} as compared with the value for wrought iron of 11.45×10^{-6}. The equality of these constants may facilitate the incorporation of β-magnesia windows into iron absorption tubes.

The Optical Constants of β-Magnesia

The ultraviolet transmission limit of β-magnesia was obtained with the aid of a Hilger E–3 quartz spectrograph and an iron arc. One of the standard 2.5-mm windows was tested. By visual comparison between the spectra taken directly and through the window it was observed that the absorption of β-magnesia is negligible to 2200A. Between 2200 and 2150A the transmission decreases very rapidly. Greatly increased exposures did not extend the spectrum beyond 2150A. Two factors which might have an effect on this limit and which were not considered were: First, the windows may have been coated with a thin layer of magnesium carbonate due to reaction with CO_2 in moist air. Second, the windows were all made from the same shipment of β-magnesia having approximately the same impurities, so that crystals having less impurity may transmit further.

The infrared transmission of β-magnesia was estimated from comparison with several crystals of known transmission to be continuous out to about 5μ or 6μ. The total energy emitted by a black-body radiator at 400°C was employed for these tests. The transmissions were measured with the aid of a vacuum radiation thermopile equipped with a KBr window. The various observed transmissions are given in Table II.

Six of the large crystals obtained from the Norton Company were ground and polished on both sides and examined for internal strain in polarized light. Optical quality was tested by observing the image of the entrance slit of a spectrometer in the telescope eyepiece after passing the light through the β-magnesia plate.

Of the six crystals tested, only one showed serious strain when observed with nicol prisms—all were of optical quality. From the remaining five, one was chosen from which two prisms were finished having faces 27×24 mm and 25×24 mm and prism angles 32° 32′ 48″ and 29° 30′ 16″, respectively. It is well to keep in mind that both prisms were cut from the same crystal, so that the following determinations are not necessarily true for crystals of different purity. It is hardly to be expected, however, that the effect of the slight impurity present would give rise to a sensible effect on the indices.

The two prisms were aluminized on the back and alternately mounted on the table of a precision Zeiss spectrometer kindly loaned by the Mount Wilson Observatory. Indices of refraction were calculated from the angular deviation of various spectral lines. The prisms were arranged after the Littrow method. In the visible the prism was set at minimum deviation for each line by the aid of a Gauss eyepiece. In the ultraviolet a quartz-fluorite lens was mounted in a box which was equipped with a slit and plate holder and the prism was set at minimum devia-

Table II. *Infrared transmission of β-magnesia crystals.*

Material	Thickness	Transmission	Limit of transmission
KCl	8.36 mm	92%	23μ
NaCl	4.64	89%	17μ
Fluorite	2.80	80%	9μ
β-magnesia	8.37	55%	estimated 5 or 6μ
Quartz	2.8	31%	4μ

Table III. *Index of refraction for β-magnesia crystals.*

	Index of refraction			
	$A=29°\ 30'\ 16''$		$A=32°\ 32'\ 48''$	
λ	Visual	Photo	Visual	Photo
2536		1.8450		
2654		1.8315		1.8316
2804		1.8171		1.8171
2967		1.8046		1.8045
3128		1.7945		1.7945
3658		1.7720		1.7720
4046	1.76132	1.7614	1.76142	1.7614
4340 (G′)	1.75531		1.75532	
4358	1.75506	1.7549	1.75514	
4471	1.75325		1.75307	
4713	1.74955		1.74940	
4861 (F)	1.74742		1.74745	
4921	1.74676		1.74672	
5016	1.74560		1.74562	
5460	1.74119		1.74126	
5790	1.73853	1.7385	1.73853	
5876	1.73787		1.73795	
5893 (D)	1.73790		1.73788	
6563 (C)	1.73364		1.73365	
6678	1.73310		1.73308	
6708	1.73304		1.73307	
7065	1.73127		1.73125	

TABLE IV. *Change of the optical constants of β-magnesia with temperature.*

λ	$n(23°)$	$n(2°)$	dn	$dn/dt\times10^5$
6563	1.73364	1.73340	0.00024	1.14
4861	1.74742	1.74711	0.00031	1.47

For other crystals:

Rocksalt	3.749
Quartz	0.649
Fluorite	1.22
Calcite	0.071

Dispersion 53.55(23°); 53.80(2°);
$d\nu=0.25$; $(d\nu/\nu)\times100=0.022$

tion photographically. The prism angles were determined by two of the three commonly used methods. The values of the indices of refraction for the spectral range λ=2536A to λ=7065A for the two prisms are given in Table III. As an additional check, the photographic settings were repeated at a few lines measured by visual settings.

In order to determine the temperature coefficient of the index of refraction, the apparatus was moved to a refrigerated room in Kerchoff Biology Laboratory, kindly placed at our disposal by Dr. T. H. Morgan, and the indices for lines *C* and *F* were measured at 2°C. The results are given in Table IV. As a control, the angle of the prism used was remeasured at 2°C and found to check with the previous value at 23°C to less than 1″ of arc.

TABLE V. *Comparison of the relative index changes for a quartz-fluorite and a quartz-magnesia lens combination.*

λ_ν and λ_τ	$\eta_\nu-\eta_\tau=\Delta n$ β-magnesia MgO	Quartz SiO_2	Fluorite CaF_2	$\frac{\Delta n_{MgO}}{\Delta n_{SiO_2}}$	$\frac{\Delta n_{SiO_2}}{\Delta n_{CaF_2}}$
2536 4046	0.0836	0.04152	0.02465	2.02	1.69
4046 4340	.00607	.00317	.00190	1.92	1.67
4340 4861	.00787	.00428	.00256	1.84	1.67
4861 5460	.00621	.00353	.00208	1.76	1.70
5460 5893	.00334	.00191	.00114	1.75	1.67
5893 6563	.00425	.00233	.00133	1.82	1.75
6563 7065	.00238	.00143	.00081	1.67	1.77

β-magnesia possesses optical properties which suggest its use in various achromatic combinations. Because of the action of CO_2 on its surface it would be necessary to cement the β-magnesia between two other components. In the case of a quartz-magnesia doublet, these outer components could both be quartz. Since β-magnesia transmits into the ultraviolet, we shall make a preliminary survey of the possibilities for its use in the particular case of a quartz-magnesia doublet lens.

The focal length of a lens with two thin components in contact is given by the relation,

$$C_a(n_a-1)+C_b(n_b-1)=1/f,$$

which can, in general, be rigorously satisfied for only two wavelengths, v and r, simultaneously. Setting up the two equations and solving for the constants gives

$$C_a=1/f(\nu_a-\nu_b)\text{, or } C_a/C_b=\Delta n_b/\Delta n_a$$
$$C_b=1/f(\nu_b-\nu_a)$$

in which the dispersion $\nu=(n_d-1)/(n_c-n_f)$, and

$$\Delta n=(n_v-n_r).$$

In order to have the focal length constant for all wavelengths, it is necessary that $\Delta n_b/\Delta n_a$ be a constant independent of the wavelength chosen for $\lambda=v$ and $\lambda=r$. This condition is never precisely fulfilled, the degree to which it is fulfilled being a measure of the suitability of the two materials for combination. The values of this ratio for various increments are shown in Table V, along with values for the usual quartz-fluorite combination. The table indicates that the secondary spectrum may deviate more for the magnesia-quartz combination than for the quartz-fluorite combination. A final appraisal of the value of β-magnesia for combination with quartz, as well as its value in various combinations with quartz, fluorite, sylvine, rocksalt or glass for doublets or triplets, is left to the opticians. It may be remarked, however, that fluorite is yearly becoming more scarce, so that there may appear a need for a cheap ultraviolet achromat where expense or availability is a greater factor than excellent color correction.

Interpretation of Data Obtained with Spectrophotometers of the Polarizing Type

ROBERT D. NUTTING,* *Massachusetts Institute of Technology, Department of Physics*

(Received March 29, 1935)

Many spectrophotometers utilize polarizing prisms and determine the reflection factor of the sample by plane polarized light. In general, the reflection factor of the sample is independent of the azimuth of the plane of polarization but there are some materials, notably textiles, for which the reflection factor depends upon the azimuth. It can be shown mathematically that, if the reflection factor is determined for two azimuths at right angles to one another, the arithmetic average of the two values is the reflection factor for ordinary, or unpolarized light. This is true regardless of the azimuths selected. Experimental data are presented which indicate the applicability of this principle to the measurement of the color of textile fabrics.

THE necessity of specifying a color by some physical means has long been realized by dyers. The difficulty of describing a color adequately in words has always been a stumbling block in the orderly solution of many of the dyer's problems. The designation of a tolerance, for example, is almost impossible if only words are used to describe the limits of this tolerance.

The fundamental method of color analysis by which a color is resolved into its elementary spectral components is known as spectrophotometry. Instruments used in making such an analysis are called spectrophotometers. Such instruments measure the proportion of the incident light that is reflected from (or transmitted by) the specimen at each wavelength of the visible spectrum. The results of such an analysis are conveniently represented by a chart on which the reflection factor (or transmission factor) is plotted against the wavelength of the light. Several such charts are presented in this paper.

In some spectrophotometers, light from a convenient source such as a tungsten lamp is dispersed into a spectrum by means of a prism. A narrow portion of the spectrum is then selected and is directed onto the sample and also onto a white standard (usually magnesium oxide). The intensity of the light reflected from the sample relative to that reflected from the standard is the reflection factor of the sample at the wavelength selected. This quantity is usually evaluated by means of a combination of polarizing prisms. The instrument used to obtain the results presented in this paper was developed by Professor A. C. Hardy and has been described briefly in a previous communication.[1] In this instrument the sample is illuminated normally by a beam of plane-polarized light, and the light reflected by the sample is collected by an integrating sphere. In some types of spectrophotometers the sample is illuminated diffusely and viewed normally, but this is an equivalent procedure.

The eye ordinarily evaluates color under natural or unpolarized illumination, whereas spectrophotometers almost invariably use plane-polarized light. It has been observed by McNicholas[2] that, even when the photometering system lacks polarizing elements, the dispersing prism alone produces a certain amount of polarization. This difference between instrumental and visual observations is of no consequence in the large majority of cases, because most samples have no polarizating effect on the light incident upon them. In other words, their reflection factors are independent of the azimuth of the plane of polarization. This paper deals with the exceptional cases that are relatively common among textile samples (practically all of the common textile fibres are birefringent) and provides a simple method for translating data obtained with plane-polarized light to a basis of ordinary illumination.

In carrying out a program of research on the spectrophotometric characteristics of dyestuffs and dyed textiles at the Massachusetts Institute of Technology,[1] fabrics which exhibit marked polarization have occasionally been encountered.

* Senior Fellow, The Textile Foundation.

[1] R. D. Nutting, J. Opt. Soc. Am. **24**, 135 (1934).

[2] H. J. McNicholas, Bur. Standards J. Research **1**, 793 (1928).

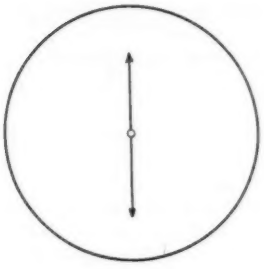


FIG. 1.

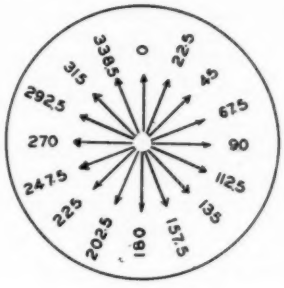


FIG. 2.

One method of obtaining the reflection factors for natural light with a polarizing instrument is to rotate the sample rapidly during its examination. A rotating sample holder has been described recently by Appel,[3] who used a visual spectrophotometer with a polarizing eyepiece, and by Shelton and Emerson[4] in conjunction with an earlier nonpolarizing type of the Hardy[5] instrument. These investigators rotated their samples to eliminate the surface effects of weave, twist, nature of warp and filling. These effects are very largely eliminated by the use of an integrating sphere. However, since it is not always convenient to rotate the sample, it was thought advisable to devise a method whereby readings made with plane-polarized light might be reduced to a basis of unpolarized illumination.

It will presently be shown that, theoretically, the arithmetic average of two measurements made with plane-polarized normally incident beams having azimuths 90° apart is equal to the value for ordinary unpolarized light. Plane-polarized light normally incident on the sample may be conveniently represented by Fig. 1. Here the sample lies in the plane of the paper and the direction of polarization for light falling perpendicularly upon it may be represented by the arrow. Ordinary unpolarized light which may be considered as light polarized in all azimuths simultaneously, may be partially represented by the diagram in Fig. 2.

To illustrate how misleading the results of a spectrophotometric analysis may be if the effect of polarization is not considered, refer to Fig. 3.

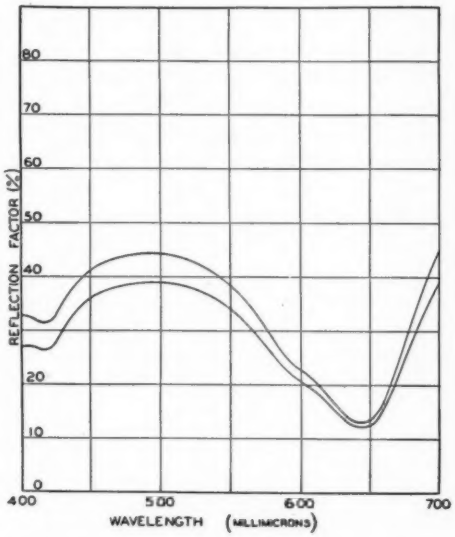


FIG. 3. Spectral reflection curves of parallel threads of green silk measured in mutually perpendicular azimuths.

This figure shows two spectral reflection curves for a single layer of parallel threads of green silk, wound eighty to the inch and measured at two positions 90° apart in azimuth. It is, of course, advantageous to know when a sample is polarizing and to have a convenient means of measuring the magnitude of this effect. However, we are now concerned with deriving the spectral reflection curve for unpolarized light, which, as stated above can be obtained by averaging the values from Fig. 3, since these observations were made at azimuths 90° apart. In order to study this effect in more detail, this sample was examined in eight positions, each position being spaced 45° from any other, and

[3] W. D. Appel, Am. Dyestuff Reptr. **17**, 49 (1928).

[4] E. M. Shelton and R. L. Emerson, Ind. Eng. Chem. Analy. Ed. **4**, 248 (1932).

[5] A. C. Hardy, J. Opt. Soc. Am. **18**, 96 (1929).

the reflection factors for each pair of measurements spaced 90° apart were averaged arithmetically. These data are presented for five arbitrarily selected wavelengths in Tables I through V.

Since normal unpolarized light is equivalent to light polarized in all possible azimuths at once, the reflection factor of this sample at any wavelength for unpolarized light is the mean of all the readings taken. This value is given in the tables and the deviations from this mean value are shown to be as high as 6 percent (where the reflection factor is 40 percent) whereas the mean deviation of the pairs averaged 90° apart is only of the order of one-half to three-quarters of one percent.

TABLE I. *Wavelength = 420 mμ.*

Azimuth (Degrees)	Reflection Factor (% *R*)	Dev. from Mean % *R*	Pairs (Degrees)	Ave. % *R* of Pairs	Dev. of Pairs from Mean % *R*
0	28.2	1.05	0 & 90	29.00	0.25
45	32.3	3.05	45 & 135	29.80	0.55
90	29.8	0.55	90 & 180	29.15	0.10
135	27.3	2.05	135 & 225	29.65	0.40
180	28.5	0.75	180 & 270	28.90	0.35
225	32.0	2.75	225 & 315	29.40	0.15
270	29.3	0.05	270 & 0	28.75	0.50
315	26.8	2.45	315 & 45	29.55	0.30
Mean =	29.25	1.59			0.33
Maximum =		3.05			0.55

TABLE II. *Wavelength = 500 mμ.*

Azimuth (Degrees)	Reflection Factor (% *R*)	Dev. from Mean % *R*	Pairs (Degrees)	Ave. % *R* of Pairs	Dev. of Pairs from Mean % *R*
0	39.8	1.24	0 & 90	40.70	0.34
45	44.4	3.36	45 & 135	41.60	0.56
90	41.6	0.56	90 & 180	40.85	0.19
135	38.8	2.24	135 & 225	41.40	0.36
180	40.1	0.94	180 & 270	40.65	0.39
225	44.0	2.96	225 & 315	41.20	0.16
270	41.2	0.16	270 & 0	40.50	0.54
315	38.4	2.64	315 & 45	41.40	0.36
Mean =	41.04	1.76			0.36
Maximum =		3.36			0.56

TABLE III. *Wavelength = 600 mμ.*

Azimuth (Degrees)	Reflection Factor (% *R*)	Dev. from Mean % *R*	Pairs (Degrees)	Ave. % *R* of Pairs	Dev. of Pairs from Mean % *R*
0	20.0	0.98	0 & 90	20.80	0.18
45	22.3	1.32	45 & 135	21.30	0.32
90	21.6	0.62	90 & 180	20.90	0.08
135	20.3	0.68	135 & 225	21.20	0.22
180	20.2	0.78	180 & 270	20.75	0.23
225	22.1	1.12	225 & 315	21.05	0.07
270	21.3	0.32	270 & 0	20.65	0.33
315	20.0	0.98	315 & 45	21.15	0.17
Mean =	20.98	0.79			0.20
Maximum =		1.32			0.33

Measurements made on a sample of green silk cloth of regular weave are shown in Fig. 4. The center curve is for the sample when rotated and the two outside curves show the spectral reflection of the sample at two azimuths 90° apart. The averaged values for eight azimuths shown in Table VI correspond very closely to the value when the sample is rotated.

The sample just considered exhibited no irregularities when averaged according to the 90° method. Fig. 5 shows the results obtained with a sample of rayon at one wavelength (400 mμ) for every 22.5° (as illustrated by Fig. 2). It is immediately seen that this sample does not obey the rule of 90° averaging. A careful inspection of the fabric disclosed that at some positions light was directly reflected into the photoelectric cell of the spectrophotometer instead of first being diffusely reflected from the

TABLE IV. *Wavelength = 650 mμ.*

Azimuth (Degrees)	Reflection Factor (% *R*)	Dev. from Mean % *R*	Pairs (Degrees)	Ave. % *R* of Pairs	Dev. of Pairs from Mean % *R*
0	12.7	0.53	0 & 90	13.10	0.13
45	13.9	0.67	45 & 135	13.40	0.17
90	13.5	0.27	90 & 180	13.10	0.13
135	12.9	0.33	135 & 225	13.35	0.12
180	12.7	0.53	180 & 270	13.10	0.13
225	13.8	0.57	225 & 315	13.30	0.07
270	13.5	0.27	270 & 0	13.10	0.13
315	12.8	0.43	315 & 45	13.35	0.12
Mean =	13.23	0.45			0.13
Maximum =		0.67			0.17

TABLE V. *Wavelength = 690 mμ.*

Azimuth (Degrees)	Reflection Factor (% *R*)	Dev. from Mean % *R*	Pairs (Degrees)	Ave. % *R* of Pairs	Dev. of Pairs from Mean % *R*
0	35.8	1.19	0 & 90	36.55	0.44
45	40.3	3.31	45 & 135	37.55	0.56
90	37.3	0.31	90 & 180	36.70	0.29
135	34.8	2.19	135 & 225	37.45	0.46
180	36.1	0.89	180 & 270	36.60	0.39
225	40.1	3.11	225 & 315	37.25	0.26
270	37.1	0.11	270 & 0	36.45	0.54
315	34.4	2.59	315 & 45	37.35	0.36
Mean =	36.99	1.71			0.41
Maximum =		3.31			0.56

TABLE VI. *Wavelength = 500 mμ.*

Azimuth (Degrees)	Reflection Factor (%)	Azimuth (Degrees)	Reflection Factor (%)
0	61.95	180	61.95
45	61.90	225	61.90
90	63.40	270	63.40
135	63.45	315	63.50
Average of 8 azimuths = 62.68		Value when rotated = 62.70	

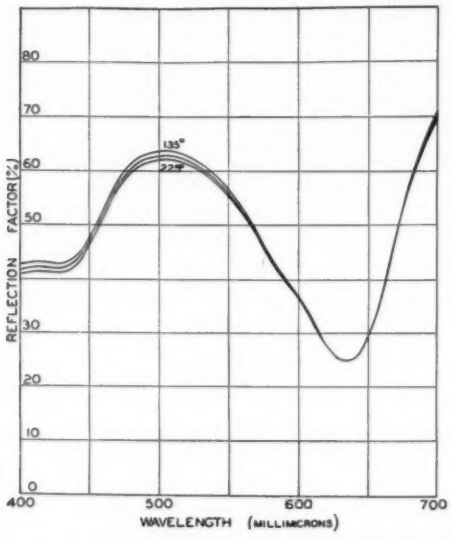


FIG. 4. Spectral reflection curves of green silk cloth. Upper and lower curves indicate mutually perpendicular azimuths. Center curve obtained with rotating sample.

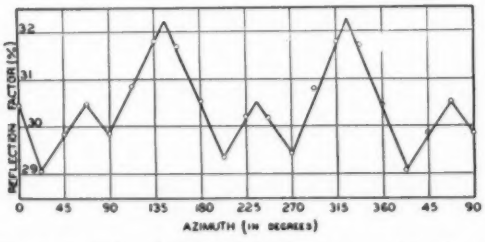


FIG. 5. Variation of reflection factor of rayon with azimuth of rotation at 400 mμ.

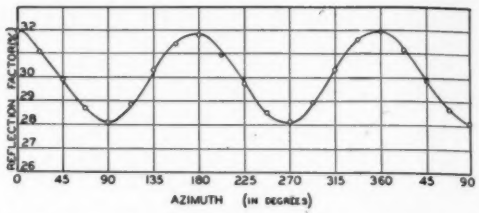


FIG. 6. Same as Fig. 5 with photoelectric cell shielded from direct spectral reflection from rayon sample.

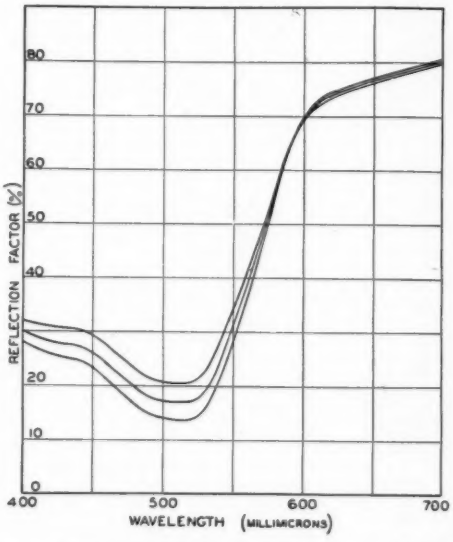


FIG. 7. Spectral reflection curve of rayon sample used for Fig. 6. Upper and lower curves indicate mutually perpendicular azimuths. Center curve obtained with rotating sample.

walls of the integrating sphere. If the photoelectric cell is properly shielded, the regular characteristic curve that would be expected is obtained and is shown in Fig. 6 for measurements made at the same wavelength (400 mμ). The spectrophotometric curves for this sample of rayon for two positions 90° apart and when rotated are shown in Fig. 7. The photoelectric cell was shielded from the direct reflection of the sample in making these determinations. Numerous other types of materials have been examined but it is impractical to present all of the results here. It may be stated however that even two-toned cloth woven from cotton and rayon or piled fabrics having the pile laid in one direction are found amenable to this method of averaging to a precision that is considered to be adequate.

A method for examining samples that exhibit polarization has been previously suggested by McNicholas.[2] He proposed to locate the plane of minimum reflection by noting the nature of the weave and to measure the sample at 45° from this position. This method is open to some practical objection; often it is not possible to locate the plane of minimum reflection of a material such as a textile fabric by a simple inspection of the weave. To locate such a position in the measuring instrument is not sufficiently precise because, at this position, the values are the least sensitive to alteration of the position. Furthermore, the minimum reflection at one

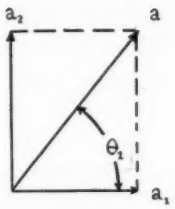


FIG. 8.

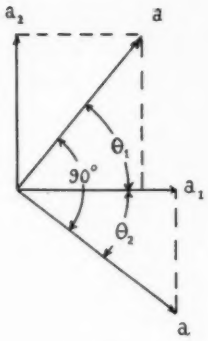


FIG. 9.

wavelength may not be the minimum at another. For these reasons it is recommended that the sample be measured in two positions 90° apart and the results averaged to obtain the reflection factor for normal, unpolarized light.

The mathematical proof of this method of averaging is given as follows. It should be stated, as a matter of practical spectrophotometry, that it is usually found more convenient to turn the textile sample through 90° rather than rotate the incident beam, but the following considerations apply equally well in either case.

Let a beam of plane-polarized light of amplitude a and intensity I be incident normally on the surface of the sample. Let this beam be resolved vectorially into two components at right angles, having the same phase and frequency. The amplitudes of these components will be referred to as a_1 and a_2 and the diffuse reflection factor of the sample in the direction of these vectors will be called R_1 and R_2, respectively.

Referring to Fig. 8, let the angle between a and a_1 be designated by θ_1. The intensity of the two components reflected by the sample are $R_1a_1^2$ and $R_2a_2^2$, respectively. The total intensity of light diffusely reflected from the sample is

$$R_1a_1^2+R_2a_2^2=I_1.$$

Since $a_1=a\cos\theta_1$, and $a_2=a\sin\theta_1$,

then $I_1=(R_1a^2\cos^2\theta_1+R_2a^2\sin^2\theta_1)$.

Now turn the beam of amplitude a through 90° so that a new angle θ_2 is made with a_1 as shown in Fig. 9. The total intensity of the light reflected from the sample in this case is I_2 whence

$$I_2=(R_1a^2\cos^2\theta_2+R_2a^2\sin^2\theta_2).$$

The average total intensity for these two positions $=(I_1+I_2)/2$, and

$$\tfrac{1}{2}(I_1+I_2)=\tfrac{1}{2}[(R_1a^2\cos^2\theta_1+R_2a^2\sin^2\theta_1)+(R_1a^2\cos^2\theta_2+R_2a^2\sin^2\theta_2)].$$

Since $\theta_1+\theta_2=90°$,

then $\cos\theta_1=\sin\theta_2$, and $\sin\theta_1=\cos\theta_2$.

By grouping similar terms and substituting

$$\tfrac{1}{2}(I_1+I_2)=\tfrac{1}{2}a^2R_1(\sin^2\theta_2+\cos^2\theta_2)+R_2(\cos^2\theta_2+\sin^2\theta_2).$$

This can be reduced to $\frac{1}{2}(I_1+I_2)=\frac{1}{2}I(R_1+R_2)$,

or $$I_{ave}=\tfrac{1}{2}I(R_1+R_2).$$

Unpolarized light may be considered as light polarized in all azimuths simultaneously and the average intensity of such a beam of reflected light may be represented by I_{ave}

$$I_{ave}=I\Sigma(R_1+R_2+\cdots+R_n)/n,$$

where $I=$intensity of light incident normally on sample, $R_n=$Reflection factor at any azimuth. The reflection factors of any of these positions (R_1, R_2, R_n) may be resolved into two components at right angles to each other and having the values $R_1'+R_2'$. Then

$$\Sigma(R_1+R_2+\cdots+R_n)/n=(R_1'+R_2')/2.$$

Therefore $I_{ave}=\frac{1}{2}I(R_1'+R_2')$. This expression is identical to the one expressing the average intensity of plane-polarized light at two azimuths 90° apart.

In conclusion, it is recommended that the spectrophotometric examination of samples exhibiting polarization be made either with the sample rotating or if this is impractical, at two azimuths 90° apart and the results averaged arithmetically to obtain the reflection (or transmission) factor for ordinary unpolarized light.

Fatigue of the Extrinsic Ocular Muscles While Reading Under Sodium and Tungsten Light

M. LUCKIESH AND FRANK K. MOSS, *Lighting Research Laboratory, General Electric Company, Nela Park, Cleveland*

(Received April 11, 1935)

THE meagerness of knowledge pertaining to the effects of spectral quality of light upon *seeing* and the voluminous literature concerning this factor and *vision* or visual functions indicates a difference between the two concepts. Vision may be defined simply as a tool for seeing and seeing as a result of a human being using this tool. The development of the sodium-vapor lamp created a situation wherein adequate data on vision proved to be inadequate for appraising the value of this new light source as an illuminant for work-world use. Therefore, it became necessary to investigate the effects of this particular quality of light from various new viewpoints. These included its actual influence upon the visibility of various work-world objects of different colors and sizes; its effect upon such physiologic variables as strain and fatigue; and its psychologic influence in such diverse realms as impressions and illusions. The result of recent investigations on several of these phases has been reported.[1]

The purpose of the investigation reported herein was to determine the relative differential, if any, in the development of "fatigue" of certain extrinsic ocular muscles which might result from reading for one hour under equal intensities of illumination from sodium-vapor and tungsten-filament lamps, respectively. The selection of reading as a visual task for this investigation does not imply that the authors seriously considered the possibility or desirability of using sodium light for such tasks, but rather because reading provides a critical, uniform, describable and controllable visual task for test purposes. Hence, a possible differential in ocular muscular fatigue would have considerable significance.

The internal recti muscles were caused to contract by means of a convergence ophthalmic ergograph, specially designed for such investigations, until diplopia or double-vision occurred. This instrument is shown in Fig. 1 and is described in detail and operation elsewhere.[2] A series of twenty successive contractions of these muscles was recorded on the drum of a kymograph immediately preceding and following each period of reading. As fatigue developed in the ocular muscles, the amplitude of these contractions, expressed in prism diopters, decreased. Hence the relative amount of fatigue developed as a result of the reading may be expressed as a difference in the amplitude of convergence of the muscles as determined from the averages of the twenty trials in each series.

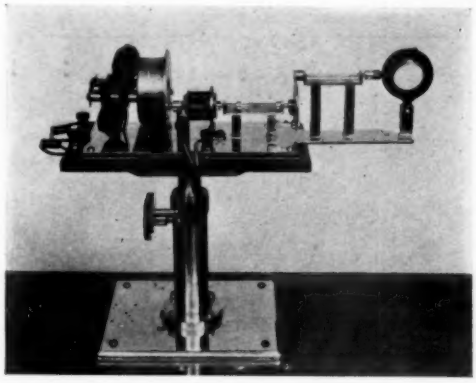


FIG. 1. The convergence ophthalmic ergograph designed by the authors for measuring the relative fatigue of the extrinsic ocular muscles. The internal recti muscles are caused to contract by varying the strength of a prism placed in the line of vision of one eye. The strength of the eye-muscles involved is determined by the "amount of prism" which can be counteracted in maintaining single vision or perfect binocular fusion.

RESULTS

The average amplitude of convergence for the several experimental conditions are summarized

[1] M. Luckiesh and Frank K. Moss, *Seeing in Sodium-Vapor Light*, J. Opt. Soc. Am. **24**, 5 (1934); M. Luckiesh and Frank K. Moss, *Visual Acuity and Sodium-Vapor Light*, J. Frank. Inst. **215**, 401 (1933); M. Luckiesh and Frank K. Moss, *Glare from Sodium Light*, Trans. I.E.S. **30**, (1935).

[2] M. Luckiesh and Frank K. Moss, *Fatigue of Convergence Induced by Reading as a Function of Illumination Intensity*, Am. J. Ophthal. **18**, 319 (1935).

TABLE I. *The individual data presented represent the arithmetic mean of four separate tests.* The corresponding relative probable errors are expressed in diopters, and do not include the systematic differences between individuals.

Subject	—*Amplitude of convergence, (diopters)*— SODIUM Before reading	SODIUM After reading	TUNGSTEN Before reading	TUNGSTEN After reading
1	22.5	19.1	22.8	20.3
2	17.7	16.6	15.8	15.7
3	18.7	18.6	18.5	18.6
4	6.2	6.1	6.3	6.5
5	18.8	15.7	18.5	15.0
Geometric mean	15.4	14.1	15.1	14.2
Probable error (diopters)	0.23	0.24	0.23	0.20
Percent decrease	8.4		6.0	

in Table I. The intensity of illumination was 5 footcandles for all conditions.

These results indicate that the amplitude of convergence is reduced approximately 6 to 8 percent by reading for one hour under 5 footcandles. It is quite probable that this method for appraising the development of ocular fatigue resulting from visual effort is only partially indicative of the actual state of these muscles. However, its value as a means for determining the relative effects on muscle tonus produced by reading under the two illuminants is not lessened by ambiguity in the absolute sense. Although the data indicate that the decrement in the amplitude of convergence is somewhat greater when the reading is performed under sodium light than it is under tungsten light, the difference is not considered particularly important because of its small numerical value and correspondingly high probable error. Since the test-method involved the continuous performance of a fairly critical and severe task for one hour, it seems reasonable to conclude that a consideration of ocular muscle fatigue is not necessary in the majority of situations where sodium-vapor light is likely to be used.

The results of a previous research[2] are interesting in connection with this experiment as well as with general lighting practice. Nine subjects read for many different periods of one hour each under one and 100 footcandles respectively, obtained from tungsten-filament lamps. The reading matter was a book printed with 8-point type and represented a visual task of far less difficulty than many common tasks such as sewing on dark goods, engraving, etc. The fatigue of the muscles of convergence after an hour's reading was about one-third as great when the level of illumination was 100 footcandles as when it was one footcandle. When it is considered that these muscles play no direct part in vision, but are essential to seeing the significance of our differentiation between seeing as a human activity and vision as a tool is emphasized. Such experiments are elevating lighting from the old basis of visibility and barely seeing toward a new basis of easy or easiest seeing.

The authors are indebted to Mr. A. A. Eastman for his part in accumulating these data.

A Recording Goniophotometer

JOHN M. SLATER, *Munsey Building, Washington D. C.*

(Received March 19, 1935)

IN studying diffuse reflection from surfaces and the angular distribution of light scattered by transmitting media, complete information can only be secured by photometry of the subject at all angles. As a matter of fact, for most subjects, ascertaining the distribution of intensity, or of brightness, at different angles throughout 180 degrees or less in the plane including the incident beam and the normal to the surface of the subject, is usually sufficient.

Jones[1] studied the variation in brightness with angle of observation for photographic papers of various types, using what he termed a *goniophotometer;* a device having means for directing a collimated (or a spreading) beam on a sample surface and a photometer arm arranged to measure the brightness of the surface. The angle of illumination could be varied and the angle of viewing held constant, or *vice versa*. Jones gives angular brightness distribution charts for various papers under illumination normal to the surface.

Measurements of this sort are tedious. The present apparatus was designed to simplify the obtaining of angular illumination distribution records. It records photographically the distribution of light reflected from a surface, over a considerable angle, in a single operation. A modification of the device is adapted for recording the distribution of light scattered from a transmitting medium.

The device in a form adapted for reflection measurements is shown in Fig. 1a, which is a diagrammatic perspective view in central vertical section. As shown, a lamp, lens and slit are provided. Light from the lamp is collimated by the lens and the beam is restricted by the slit, so that a thin ribbon of light is directed upon the suitably mounted sample surface, at an angle of 45 degrees to the normal. The device can readily be modified to employ some other angle of incidence. The beam produces a narrow illuminated area or "line" on the sample surface. An optical wedge, in the form of a quadrant (approximately) of a cylinder, is mounted over the sample, as shown, with the axis of the cylindrical wedge coinciding with the illuminated line. The wedge grades in opacity from one side to the other, along the direction of the axis.

To make a record, the sample is put in place, the light is turned on, and a piece of photographic film or paper is held against the wedge in the position shown, and is exposed. The developed paper has graphically recorded thereon, in a manner similar to wedge spectrograms, the angular distribution of illumination, at the wedge, produced by the illuminated line on the sample.

The wedge used was graded logarithmically in opacity steps ($Q=1/T$; $\log_{10} Q=D$; where $Q=$opacity, $T=$transparency and $D=$density) and was made by suitably exposing a photographic film in steps. It was found that for best results the opacity of each step should be rather less than twice that of the preceding step. The

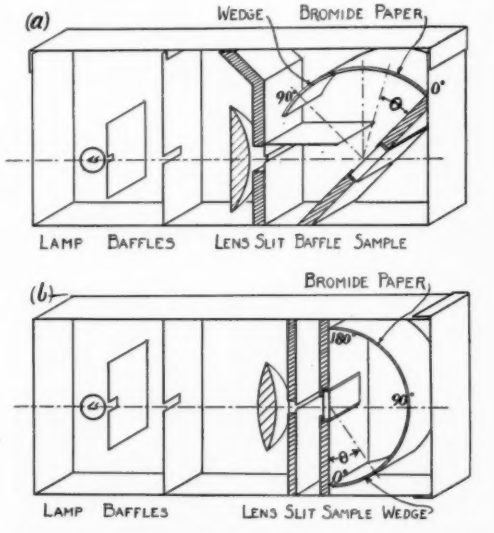


FIG. 1. Diagrammatic views of the goniophotometer for reflection measurements (*a*) and as modified for transmission measurements (*b*).

[1] L. A. Jones, *The Gloss Characteristics of Photographic Papers*, J. Opt. Soc. Am. **6**, 140 (1922).

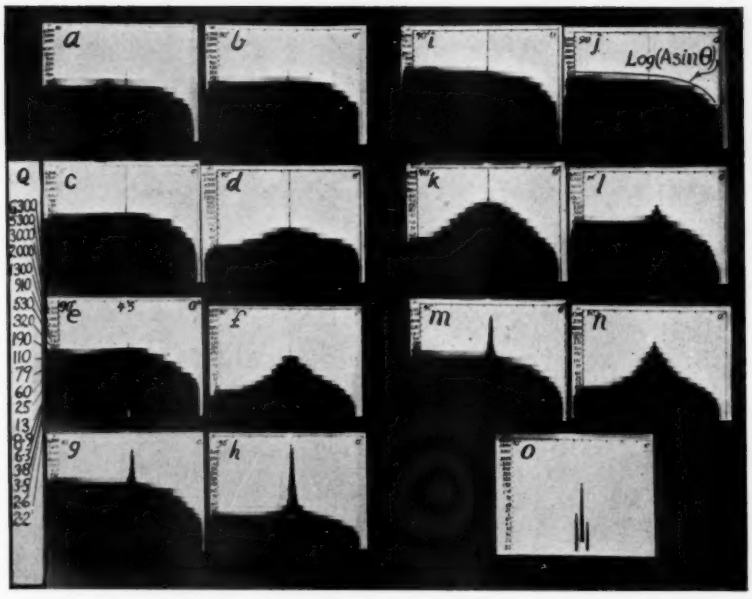


FIG. 2. Reflection records for (*a*) white blotting paper; (*b*) J. Opt. Soc. Am. paper (December, 1934 issue); (*c*) matte bromide paper (Portrait Bromide, Rough Luster), white tone; (*d*) the same, black tone, same exposure as for (*c*); (*e*) semi-matte contact paper (Vitava Athena B Smooth White), white tone; (*f*) the same, black tone, same exposure as for (*e*); (*g*) glossy bromide paper, ferrotyped, white tone; (*h*) the same, black tone, same exposure as for (*g*); (*i*) scraped plaster of paris block; (*j*) the same, with the function log ($A \sin\theta$) drawn on the record; (*k*) aluminum paint on tinned iron; (*l*) light gray semiglossy paint on tinned iron; (*m*) light gray glossy paint on tinned iron; (*n*) reflection from emulsion surface of a heavily fogged, fast plate (Wratten Hypersensitive Panchromatic); and (*o*) reflections from a second-surface-silvered mirror.

Abscissae are the angles θ. Angle of illumination = angle of specular reflection = 45 degrees. Opacities of the wedge steps are marked on the left side of the records.

wedge used in making the records shown in Fig. 2 (to be described) has opacity steps grading as about 1.7 to 1, which is a little coarse for distinguishing among very matte materials. It was found that for general work with surfaces such as are encountered on photographic papers the wedge should have an opacity range of the order of 1 : 5000 or 1 : 10,000, while for very matte materials the range can be narrower.

In the apparatus as constructed the active portion of the wedge was 8×12 cm and the device took a sheet of bromide paper 10×12.5 cm (4×5 inch). The slit was 8×0.2 cm and the sample size was 8.5×2 cm. The principal focus of the lens was about 14 cm.

Assuming a collimated beam and a small lens aperture, for a specularly reflected beam the illumination at the wedge, along the axial length of the wedge, would be uniform. But for the diffuse component of light reflected from a sample surface, the illuminated area on the sample is in effect a diffusely emitting surface; a line source of finite length; and the illumination at the wedge falls off from the center toward each end of the wedge. But at points near the central region of the wedge, illumination is practically constant axially, and the records can be brought in this region, which practically avoids errors due to this effect. This error could be further reduced by shortening the slit and wedge, while keeping the same radius wedge.

It is quite important to suppress stray light, which vitiates the records. The three baffles shown in Fig. 1a were all found to be necessary. The degree to which stray light has been cut down can be tested by making an exposure with a mirror in the sample position. There should be no indication of diffuse reflection, when an ex-

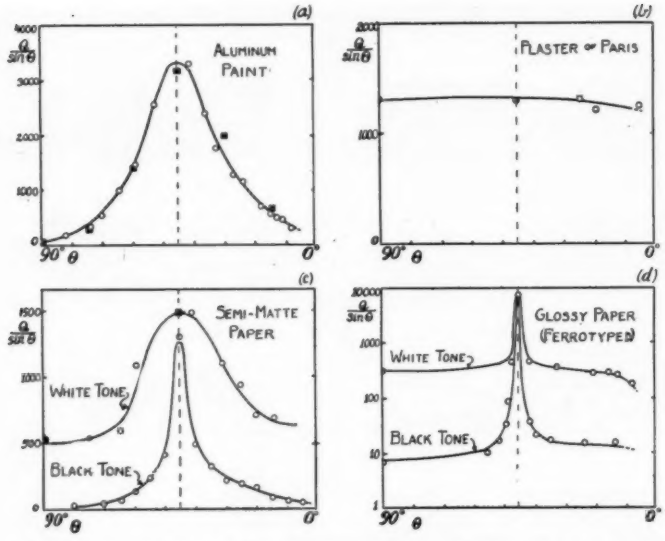


FIG. 3. Values of $Q/\sin\theta$ plotted against θ for (*a*) aluminum paint on tinned iron; (*b*) scraped plaster of paris block; (*c*) semi-matte contact paper, white and black tones (Vitava Athena B Smooth White); and (*d*) glossy, ferrotyped bromide paper, white and black tones, the values for $Q/\sin\theta$ in this case being plotted on a logarithmic scale, for clarity. The squares represent brightness values as determined with a visual photometer.

posure is made so as to bring the record made by the reflected beam, into the deepest opacity step of the wedge. Fig. 2, (*o*), is a record made of a narrow second-surface-silvered mirror in the sample position, in the apparatus described.

The lamp was a 6 cp., 6–8-volt bulb, which was run at 8 or 9 volts to shorten exposure times. The semicircular filament was aligned with the slit.

In making an exposure the sample is put in place and a piece of sensitive material is pressed against the wedge. Glossy bromide paper of "contrast" or "extreme contrast" grade works well. Using process film for the record, and printing therefrom on contrasty paper, gives a sharper record, but is more costly and troublesome. Exposure times using bromide paper were 3 to 20 minutes.

Fig. 2 shows records made direct on bromide paper, of reflections from various samples as labeled. The measured (diffuse) opacities of the steps of the *wedge*, and angles θ measured from the plane of the surface (*cf.* Fig. 1), are marked thereon. For legibility, the opacity values for one of the records (*e*) are indicated in large scale at the left of the figure.

The opacity values are read for the faintest trace of developed silver image. It helps in reading to sketch a curve enveloping the image. Assuming that illumination at the wedge is proportional to the intensity of radiation from the narrow illuminated line on the sample, then opacity at a given angle θ may be taken as directly proportional to intensity. With this assumption, to find brightness, the opacity value at each ordinate is divided by $\sin\theta$.

Fig. 3 shows distribution curves for aluminum paint, scraped plaster of paris, and two types of photographic papers as labeled; the curves being obtained by plotting the observed opacity values from the corresponding records, divided by $\sin\theta$, against θ. The squares represent brightness measurements (relative values) obtained with a visual photometer. The agreement is fairly good for aluminum paint and the semi-matte paper. But the records give a brightness ratio, between $\theta=45$ degrees and $\theta=90$ degrees, of about 30 to 1, for the glossy paper, while the visual photometer indicates a ratio of about 90 to 1. Possibly the different reflection characteristics of the

sample for the visual region and the photographic region, play a part in this discrepancy.

Using a wedge grading logarithmically in opacity, then for a perfectly diffusing surface obeying Lambert's law of emission ($I = I_n \cos \phi = I_n \sin \theta$, where ϕ is the angle between the reflected beam and the normal), the curve indicated in the records should have the *shape* of log sin θ *versus* θ. Fig. 2, (*i*), is a record for scraped plaster of paris, which is a good diffuser, and (*j*) is a similar record, with the function log (A sin θ) marked thereon, A being taken as the opacity value at $\theta = 90$ degrees in the record. The ordinate for the curve at 90 degrees was log $Q = \log A$; and the ordinate at one other angle was taken as log Q at that angle. The curve shape of (*i*) and (*j*) is characteristic of the records of the diffusely reflected components from highly glossy materials; cf. (*g*) and (*m*) of Fig. 2.

This particular device was made to measure distribution over an angle θ of about 5 to 100 degrees.

The device is readily modified for transmission work. Fig. 1b is a sketch in perspective vertical section of a transmission instrument, covering an angle θ of 180 degrees. The slit width was 0.3 mm and the active area of the wedge was 5×11 cm.

Fig. 4 shows records made with this device, of several different materials as labeled. Records (*e*) and (*f*), of angular distribution of light scattered from photographic plates, should be compared with record (*n*) in Fig. 2, of reflections from the surface of a heavily fogged fast plate. They indicate an angular distribution of scattered light quite different from the more or less independent specular and diffuse components as observed in reflections from glossy surfaces: Fig. 2, (*g*) and (*m*).

Fig. 5 shows graphs of the logarithm of the opacity values taken from some of the records of Fig. 4, that is, density ($D = \log Q$), plotted against angle θ. The ordinates in Fig. 5 are proportional to the logarithm of the intensity. The curve shapes of Fig. 5 would appear directly in the photographic records, were the wedge graded perfectly logarithmically.

The two embodiments of the device, while perhaps not capable of the accuracy obtainable in visual photometry, have the advantage that the distribution is recorded quickly and in a single operation, and is graphic. The device has the advantage that with long exposure it can record very faint scattered components; too faint for visual measurement. It is believed the apparatus may have utility in studying gloss characteristics of surfaces, and in studying light scattering in turbid media such as colloidal solutions.

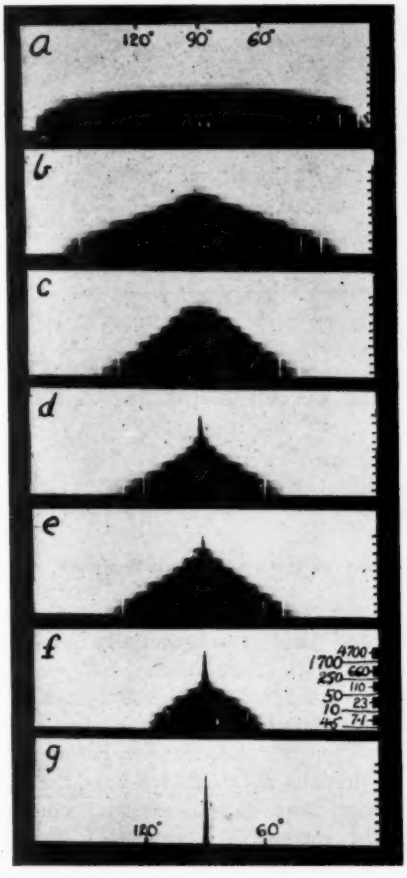


FIG. 4. Transmission records for (*a*) flashed opal glass; (*b*) strong soap solution, 2 mm thick; (*c*) leader strip for 16 mm moving picture film (matte-surfaced acetate stock); (*d*) liquid glue, 1 mm thick; (*e*) Wratten Hypersensitive Panchromatic plate, light fog; (*f*) process plate, light fog; and (*g*) blank, for comparison.

The white lines along the base of the records indicate 10 degree steps. Opacities of the wedge steps are marked on record (*f*).

The apparatus was designed primarily for measuring reflections from photographic papers

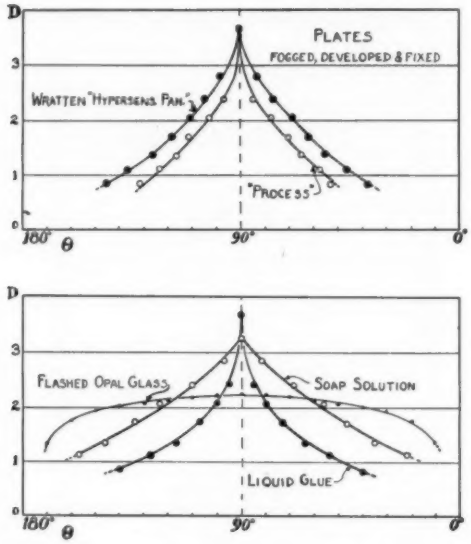


FIG. 5. Values of $D(=\log_{10} Q)$ plotted against θ, for records (*a*), (*b*), (*d*), (*e*) and (*f*) of Fig. 4.

and coated papers: substantially nonselective materials. With these things, as with most coated materials, it happens that the surface is optically smoother, so to speak, than the mass of fibers, pigment particles, etc. below the surface; so that the light reflected from the surface contributes more to the specular component while light reflected from below contributes more to the diffuse component. With nonselective materials, the character of light reflected from the surface is the same as that of light reflected from the fibers, etc., below. Thus light reflected from such materials in any direction has the same character. Therefore, while the net spectral sensitivity function for bromide paper is different from the luminosity curve for the eye, and has a maximum at about 450 mμ (with the tungsten filament lamp used) as compared with the maximum at about 560 mμ in the case of the eye, bromide paper records of reflections from such materials are in most cases consistent enough with visual measurements for practical purposes.

In many selectively reflecting (colored) materials, however, light reflected from the surface is practically the same in character as the incident beam, while light reflected from the dyes, pigments etc. below the surface is colored. (Metals and certain dyes are exceptions.) Light from the surface is commonly scattered less than light from below. As a result, the scattered light is colored differently from the light reflected at or near the specular angle; and usually the greater the angle of scattering of the light, the more colored it is.

Similar considerations apply to transmitting media.

In measuring such materials with the present apparatus, this variation of color with angle must be taken into account, as with any other goniophotometer. This is done by employing, instead of bromide paper, panchromatic film, in conjunction with the appropriate orthochromatic filter, which is best placed over the second baffle from the left in Figs. 1a and 1b. Eastman

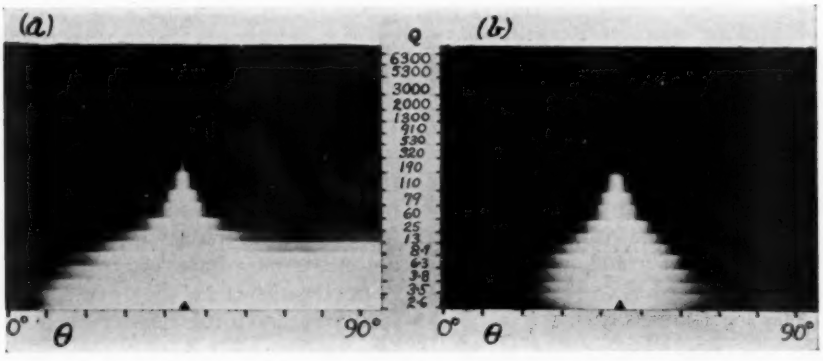


FIG. 6. Prints from records on panchromatic film, of reflections from a semiglossy orange-red painted sample, (*a*) with an orthochromatic filter and (*b*) with a deep blue filter.

panchromatic process film with a Wratten K2 filter is a suitable combination, using the source described. The net spectral sensitivity function of the proper film-filter-source combination is very similar to the luminosity function of the eye. The film should be developed to the highest practicable contrast, and printed on high contrast paper; e.g., "Azo F No. 5."

Fig. 6a shows a print from a negative record on panchromatic film, of reflection from a sample of semiglossy, high saturation orange-red paint on tin, with the proper orthochromatic filter.

When the color of a sample is fairly saturated, it is possible by the use of suitable contrast filters to isolate, to a considerable degree, the surface-reflected component; so as to measure its "spread" for example. Fig. 6b shows a print from a record of the sample of Fig. 6a, on panchromatic film, using a deep blue filter (Wratten C4) so as to suppress reflected orange-red light. The record represents mainly surface-reflected light.

A record of this sample made directly on bromide paper (maximum sensitivity at about 450 mμ) would resemble Fig. 6b.

If it were desired to make angular distribution records with monochromatic incident light, the narrowed slit of a monochromator might be substituted for the lamp in the apparatus shown in Fig. 1.

Back Numbers Wanted

THE OPTICAL SOCIETY OF AMERICA will pay one dollar per copy for each of the following issues:

Volume 8, No. 2—February, 1924
Volume 16, No. 1—January, 1928
Volume 18, No. 2—February, 1929
Volume 18, No. 3—March, 1929
Volume 18, No. 5—May, 1929
Volume 19, No. 1—July, 1929
Volume 19, No. 2—August, 1929
Volume 19, No. 3—September, 1929
Volume 19, No. 4—October, 1929
Volume 19, No. 5—November, 1929
Volume 19, No. 6—December, 1929

Copies should be addressed to the American Institute of Physics, 11 East 38th Street, New York, New York, with the name and address of sender and with a covering letter.

Annual Report of the Secretary of the Optical Society of America for the Calendar Year 1934

Membership Record

January 1, 1934 to January 1, 1935

	Honorary	Regular Annual Payment	Regular Life Payment	Associate Individual Annual Payment	Associate Corporation	Total
Membership as of record in the books of the Secretary and Treasurer 1–1–34	4	412	6	199	10	631
Gains during 1934						
By election during 1934 as of 1–1–34	0	0	0	18	0	18+
By election as of 4–24–34*	0	1	0	0	0	1+
Losses during 1934						
By death	0	0	0	1	0	1−
By resignation as of 1–1–34	0	6	0	7	1	14−
By separation for non-payment of dues	0	6	0	17	0	23−
Membership as of record 12–31–34	4	401	6	192	9	612
Gains between 12–31–34 and 1–1–35						
By election during 1934 as of 1–1–35	0	0	0	7	0	7+
By transfer 10–17–34 as of 1–1–35	0	15	0	0	0	15+
By transfer to regular life membership	0	0	1	0	0	1+
Losses between 12–31–34 and 1–1–35						
By transfer 10–17–34 as of 1–1–35	0	0	0	15	0	15−
By transfer to regular life membership	0	1	0	0	0	1−
By resignation during 1934 as of 12–31–34	0	6	0	5	0	11−
Membership as of record 1–1–35	4	409	7	179	9	608

* The Lord Rayleigh, President of the Physical Society of London, made ex-officio member.

Elected during 1934 as of January 1, 1934

Ernst H. Anthes (951 A)
J. A. Ball (964 R)
Harold R. Bellinson (966 A)
Laurence Burns (963 R)
Alan A. Cook (957 A)
Myrl N. Davis (959 A)
George Graham Harvey (975 A)
R. M. Holmes (965 A)
Gjon Mili (952 R)
Osborn M. Miller (954 A)
Robert D. Nutting (967 A)
John E. Perry (962 A)
Maurice Ricker (953 A)
Edwin G. Schneider (955 A)
Cyril J. Staud (961 R)
Luville T. Steadman (958 A)
Richard Tousey (956 A)
Walter Wrigley (960 A)

Elected during 1934 as of April 24, 1934

The Lord Rayleigh, President of the Physical Society of London, made ex-officio member

Elected during 1934 as of January 1, 1935

James F. Angier (972 A)
Mario Bossolasco (968 A)
Edward O. Hulburt (970 R)
Thomas J. Killian (969 A)
Howard C. Lindemann (971 A)
Gerald Kent Neeland (974 A)
Francis Leo Talbott (973 A)

Elected to Regular Membership by Action of the Board of Directors October 17, 1934, Effective January 1, 1935

Carl E. Bahn (942 R)
J. A. Ball (964 R)
Vola Price Barton (757 R)
Julian M. Blair (948 R)
F. Chapin Breckenridge (594 R)
Brooks A. Brice (882 R)
Laurence Burns (963 R)
Gordon A. Chambers (474 R)
J. H. Ellis (494 R)
Gustave Fassin (943 R)
David L. Gamble (950 R)
E. O. Hulburt (970 R)
David L. MacAdam (930 R)
Gjon Mili (952 R)
Cyril J. Staud (961 R)

Death during 1934

Roy Y. Ferner (224 A)

Resignations during 1934 as of January 1, 1934

William Berry (675 R)
A. K. Chapman (87 R)
Thos. E. Doubt (766 R)
F. Lowell Dunn (568 A)
E. Gilbert Dymond (769 A)
Louis Harris (883 A)
Axel G. Jensen (792 A)
David A. Keys (801 R)
R. E. Lofton (535 A)
Robert A. Patterson (670 R)
Technicolor Motion Picture Corp.
Geraldine Kline Walker (550 A) (656 AC)
Frank Walter Weymouth (329 R)
Remsen V. Wood (905 A)

Resignations during 1934 as of December 31, 1934

E. J. Brady (339 R)
Charles A. Corcoran (780 A)
Harry R. DeSilva (701 R)
Gordon S. Fulcher (277 R)
Lloyd Logan (482 A)
William F. Roeser (835 R)
F. F. Rupert (567 R)
L. P. Sieg (214 R)
David L. Soltau (746 A)
Charles Gormley Stehle (685 A)
B. A. Wooten (522 A)

(*Signed*) L. B. TUCKERMAN, *Secretary*

Optical Society of America, Inc.

STATEMENT OF CASH TRANSACTIONS, JANUARY 1, 1934 TO DECEMBER 31, 1934

Receipts		
Dues	$2,419.73	
Dues in advance	1,150.00	
Unbudgeted Income	1,448.98	
Interest on Bonds	836.65	
Interest on Bank Accounts	175.94	
Ives Medal Fund Income	21.25	
Adolph Lomb Memorial Fund Income	45.00	
Unredeemed 1933 Check, etc.	9.41	
		$ 6,106.96
Disbursements		
Secretary's Expense	$ 549.99	
Secretary's Travel Expense	37.68	
Treasurer's Expense	116.48	
Journal Publication Expense	1,520.11	
Journal Editorial Expense	925.00	
Contingencies	25.00	
Adolph Lomb Memorial Fund Principal	2,000.00	
		$ 5,174.26
Cash Increase January 1 to December 31, 1934	$ 932.70	
Cash in bank January 1, 1934	7,249.75	
Cash in bank January 1, 1935	$8,182.45	
Adolph Lomb Memorial Fund Principal	2,000.00	
Total cash on deposit January 1, 1935		$10,182.45

Ives Medal Fund

Principal	$ 500.00	
Balance January 1, 1934	46.04	
Income, 1934	21.25	
		$ 567.29

Adolph Lomb Memorial Fund

Principal	$2,000.00	
Bank Interest, 1934	45.00	
		$2,045.00

1934 Optical Society Investments

	Control Value	Cost	Market, Dec. 1, 1934
7000 Atchison Topeka and Santa Fe	$ 7,000	$ 6,916.25	$ 7,367.50
8000 Fourth Liberty Loan 4¼	8,000	8,144.64	8,170.00
5600 U. S. A. Treasury Certificates	5,600	5,625.67	5,708.50
	$20,600	$20,686.56	$21,246.00

Sale and Purchase Transaction

Sold $2000 Fourth Liberty Loan Bonds 4¼'s Called @ 102	proceeds	$2040.00
Bought $2000 Treasury 4¼–3¼'s Due 1945 @ 102$\frac{23}{32}$	cost	2058.13
Net loss due to change		$18.13

(*Signed*) Henry F. Kurtz, *Treasurer*

February 18, 1935

The undersigned, having been duly appointed to audit the books of the treasurer of the Optical Society of America from January 1, 1934 to December 31, 1934 hereby certify that the treasurer's official report of receipts, disbursements and investments is correct as shown by records, bank statements, vouchers, etc.

(*Signed*) Carl L. Bausch
C. W. Frederick